INTRODUCTORY REMARKS

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On a number of occasions such as this, one of the many advantages of representing the fluid mechanics research area is that it generally puts one at the beginning of the program agenda with its attendant benefits. Fluid mechanics has such a place, of course, because it deals with fundamentals which underlie the various aerodynamic specialties. In order to avoid extensive overlap with the other panels, it is suggested that the fluid mechanics area be considered as concerned with research to provide insight and understanding of phenomena involved in practical aircraft problems. By contrast, the rational use of data generated from the applied aerodynamics areas is limited only to the specific configuration tested and to the range of parameters covered. Thus, the approach to testing in fluid mechanics is to obtain generalized information, which in many cases can be obtained by the use of simplified models and idealized configurations.

In considering the test programs for the National Transonic Facility (NTF), the unique capabilities of cryogenic tunnels and the NTF in particular (fig. 1) should be kept in mind and taken advantage of. Obviously, the tests should explore high Reynolds number effects. More than that, however, and in contrast to the manner in which tests are run in existing tunnels, the tests should investigate viscous (that is, Reynolds number) effects independently of compressibility effects or aeroelastic distortion. This unique capability of the cryogenic tunnel is illustrated in figure 2 where it can be seen that the ratio of the test-section dynamic pressure q to the model modulus of elasticity E can be held constant as Reynolds number is increased. This test capability eliminates the variation of model shape with changing Reynolds number that occurs in noncryogenic tunnels. In addition, although of lesser priority, studies should be made of compressibility (that is, Mach number) effects independently of Reynolds number or aeroelastic effects (fig. 3).

With the preceding thoughts as a guide, suggested fluid mechanics research areas for the NTF are listed in figure 4. The basic problems shown in the top grouping are ubiquitous phenomena which underlie almost all practical aerodynamic problems that arise in the design of modern aircraft. The second grouping of items are tunnel-related effects which tend to obscure the aerodynamic results obtained in conventional tunnels. By investigating and isolating such effects in the NTF, it should be possible to increase the usefulness of existing tunnels. The third item listed in the figure emphasizes the importance of using the new tunnel for experiments which are expressly designed to provide empirical inputs or validation data for computational aerodynamics. To the extent that the future can be predicted at all, it seems clear that aerodynamic theory is becoming less of an adjunct and more of a partner to experiment in aircraft design, and this role must be recognized through more selective test programs which take fullest advantage of the capabilities of both partners.

Detailed test programs should be examined and proposed for all the areas listed in figure 4. These programs can be illustrated briefly with a few examples. Turbulent skin friction must be looked at in the manner shown in figure 5. Of all the parameters shown, flat-plate Reynolds number effects are most basic, and an extension of the test data shown in figure 6 should be considered as an early priority.

Data are needed on the detailed characteristics of the turbulent boundary layer prior to, during, and following the interaction with a shock wave. The most useful information might be that obtained in a systematic investigation at both high and low Reynolds numbers on a supercritical airfoil of current interest (fig. 7). Specifically, the following boundary-layer characteristics are of interest: effects of Reynolds number on shock location, effects of chordwise extent of supercritical flow and Reynolds number on trailing-edge separation, and effects of Reynolds number on off-design characteristics. Although, for the case shown, the two-dimensional transonic theory shows changes in shock location to continue at Reynolds numbers beyond NTF capability, it should be noted that a most important part of the investigation could probably be carried out two-dimensionally in the Langley 0.3-m transonic cryogenic tunnel. Obviously, it should be kept in mind that the smaller cryogenic facility or other existing facilities should be utilized to the greatest extent possible for "precursor" testing in order to reduce the test load on the NTF.

In addition to shock-induced separation, viscous separation resulting from cross flows is extremely important in high-angle-of-attack flight dynamics for both aircraft and missiles. As shown in figure 8, Reynolds number can change drastically the forces and moments acting on both simple two-dimensional bodies and complete aircraft. These two cases are related to the same phenomena, and basic studies on the nature of viscous separation at high Reynolds number and high subsonic speeds are very much in order. Another type of flow separation is shown in figure 9, in which the separation occurs at the leading edge of delta wings. In such cases of practical interest, the separation leads to a vortex system which provides large vortex-lift increments and greatly alters the pressure distribution over the wing and thus dominates the flow field. For rounded leading edges, the effect of Reynolds number on the vortex-lift characteristics can, of course, be very large and high Reynolds number data are needed. However, even for the sharp-leading-edge case illustrated in figure 9, the effect of Reynolds number on the secondary vortex can be appreciable for the very slender wing case. For this case high Reynolds number data are needed to establish the full-scale surface load distributions and to verify the suction analogy theory as the true asymptote for the overall lift. Generalized research is needed in this area to investigate such phenomena as primary and secondary vortex separation and reattachment, vortex breakdown and asymmetry, and multiple (that is, fuselage and wing) vortex interference.

An example of the potential of the NTF to evaluate and improve the capability of existing transonic facilities is shown in figure 10. This figure shows that the wide range of temperatures available in the NTF can be used for tunnel-wall interference studies by testing models of various sizes at constant Mach and Reynolds numbers and constant dynamic pressure. (Interference studies in existing tunnels, in contrast, would involve extraneous aeroelastic or Reynolds number effects in attempting to use the large and small model approach.)

It is appropriate to conclude these remarks with a reminder that dynamic-pressure changes during Reynolds number tests in conventional tunnels may mask or dominate true Reynolds number effects. Examples are shown in figure 11. In the left side of the figure, the aeroelastic deflection of the aft portion of a supercritical airfoil model is shown to cause a significant shift in chordwise shock location. In the right side of the figure, the increase in dynamic pressure which was required for a modest increase in the Reynolds number from 2×10^6 to 3×10^6 resulted in a change in aeroelastic distortion sufficient to cause a large forward movement of the shock, instead of the aft movement which would be expected from the increase in Reynolds number. Thus, the NTF with its unique ability to isolate effects of Reynolds number and aeroelasticity will provide information that will aid in the proper interpretation of data obtained at lower Reynolds numbers in conventional tunnels.

PANEL CONSIDERATIONS AND RECOMMENDATIONS

Samuel Katzoff

DEGREE OF EFFORT IN BASIC STUDIES

In most NASA wind tunnels, even in those that are heavily involved in studying specific configurations, a certain amount of effort is devoted to fairly basic studies. Such studies, which are often suggested by the results of the configuration tests, are made not only to help understand the results of the tests but also to obtain information applicable to other configurations. In a unique national facility like the NTF, however, the pressures for ad hoc testing may be so strong that studies directed toward understanding the basic aerodynamic phenomena and thus generalizing the results of the ad hoc tests could be forced into very low priority. Long-term gain would thus be sacrificed to immediate needs.

These anticipated pressures ought to be resisted to the extent necessary for relevant basic studies. Where feasible, the configuration studies themselves might be extended in order to clarify the aerodynamics associated with the measurements. More basic studies with special, idealized models must also be included. It is estimated that 10 percent to 15 percent of the total time and effort could profitably be dedicated to such basic studies.

WIND-TUNNEL CALIBRATION

For a wind tunnel like the NTF, which is intended to provide very exceptional capabilities, the nature of the test-section flow is a matter of particular moment. A number of items in the NTF design and in its anticipated characteristics merit special consideration in this regard.

The high anticipated noise level at full power, 150 dB, has occasioned concern that the noise could affect boundary-layer transition or separation, although turbulent skin friction would not be affected. Actually, present information indicates that a nominal 150 dB level is somewhat too low to affect transition although the certainty of this conclusion may somewhat depend on the noise spectrum. When the superimposed effects of stream turbulence and tunnel vibration are considered, however, any reduction in noise level would be reassuring. Some help may be available from noise-reduction experience at other facilities (Arnold Engineering Development Center (AEDC); also some British wind-tunnel work). Rounding the test-section slots is also known to reduce noise. In any case, the NTF noise spectrum should be determined for both the slots-open and slots-closed conditions, and a similar determination should be made for the Langley 0.3-m transonic cryogenic tunnel.

The settling chamber in the present design is considered somewhat too short to achieve much smoothing out of a very rough and irregular entering flow. Three screens may not suffice to eliminate the remaining roughness and flow nonuniformity and to provide a smooth, low-turbulence test stream. This problem should be thoroughly studied well before the tunnel design is fixed, probably with the aid of a model tunnel.

In the conversion of the Langley 19-ft pressure tunnel to the present Langley transonic dynamics tunnel (TDT), the enlarged nacelle caused some degradation of the flow in the long return leg; however, model tests showed where to install a low-pressure-drop screen in this leg in order to prevent separation of this flow. No reduction in tunnel efficiency seemed to result from installation of this screen. Another method of avoiding boundary-layer separation on the wall of a return passage is to use the pressure of the air (or gas) in the tunnel to blow out some of the boundary layer through slots just ahead of the separation region.

To some extent, comparison of data obtained in the NTF with reputable data previously obtained in other high Reynolds number wind tunnels will aid in certifying the NTF and its test techniques; however, good agreement at lower Reynolds numbers cannot be assumed to extend to the higher Reynolds numbers that only the NTF can attain, especially since the tunnel noise and vibration increase rapidly as maximum power is approached. For these studies it would be advisable, at subcritical Mach numbers at least, to make measurements both with the test-section slots open and with the slots closed. In the latter condition, the noise, and perhaps flow irregularity and turbulence, should be reduced so that the flow deterioration in the slots-open condition could be thereby evaluated.

One test article that is now available for intertunnel comparisons is the 10° cone that Steinle and Dougherty have been testing in various facilities. Other suitable models should also be available.

Precise relationships of stream turbulence characteristics to transition and separation may not now be clearly defined. In any case, a thorough study of the turbulence and other flow nonuniformities in the test section, as a function of pressure, temperature, and Mach number, and with slots open and closed, ought to be included in the initial tunnel calibration. Furthermore, periodic recalibration of the tunnel is advisable since tunnel characteristics may change with time.

Finally, it should be noted that tunnel calibration will be intimately involved in other research areas (for example, skin friction and wind-tunnel interference). Hence, it will hardly be considered as a finished project after the initial calibration studies have been made.

FLAT-PLATE SKIN FRICTION

An important fundamental study, which would also tie in with the tunnel certification, is the determination of skin friction on a flat plate. Present data extend to Reynolds numbers of about 5×10^8. A 6-meter flat plate in the NTF could provide Reynolds numbers up to 3×10^9. However, where high Reynolds numbers are obtained by increased gas density and lowered viscosity, turbulent skin friction is especially sensitive to surface roughness. In the NTF at the highest unit Reynolds number, the roughness effect on turbulent skin friction is estimated to begin when roughness exceeds 2×10^{-5}cm (8×10^{-6} inches). The 6-meter-long surface, if polished to this degree, will be expensive if made of metal; a sheet of plate glass may be more practical. Such definitive skin-friction studies at high Reynolds numbers have important practical applications. It has been stated that a 10-percent difference in skin friction can correspond to the difference between successful and unsuccessful operation of a big airplane.

Certain basic boundary-layer and skin-friction studies at high unit Reynolds numbers can be done more simply and more cheaply in the Langley 0.3-m transonic cryogenic tunnel (both with slots open and slots closed) or in other wind tunnels. Among such studies are those concerning the effects of roughness and waviness on transition and skin friction. In particular, the above-mentioned estimate of the maximum allowable roughness for a smooth surface needs to be verified, not only as basic research but also so that the surface finish on test models can be specified. The nature and extent of the noncharacteristic turbulent boundary layers just downstream of transition strips also have to be studied. Some of the results might be verified in the NTF as part of the calibration studies.

FLOW-VISUALIZATION AND MEASUREMENT TECHNIQUES

Flow-visualization methods have been useful for both qualitative and quantitative understanding of aerodynamic phenomena, and efforts must be made to adapt these methods to the low temperatures of the NTF. The vapor-screen method seems especially to deserve some concentrated development effort, although it is not yet obvious that a suitable substance for these temperatures exists. An appropriate "smoke" should also be sought since localized smoke injection has often been useful in identifying very local phenomena. Both of these methods contaminate the flow; however, since there is continuous exchange with fresh nitrogen, some degree of contamination should be acceptable.

There is probably no substance that can serve as the "oil" for surface oil-flow studies. Substances might be found, however, that are suitable for the sublimation method. This method can differentiate turbulent-flow areas from laminar-flow and separated-flow areas, but cannot, in general, show local flow directions. Infrared observations of surface temperatures using a liquid-helium-cooled detector may also serve to differentiate laminar-flow areas from turbulent-flow areas at transonic Mach numbers.

Methods of measuring local velocities and directions, quantitatively and with known accuracy, need to be developed. Intrusive devices - hot wires and survey tubes - are well known, although the high pressures and the thin boundary layers in the NTF greatly increase the difficulty of use. There are high hopes for the laser-doppler velocimeter (LDV), since it is a remote-observation, nonintrusive device. It is already a useful tool, and by the time that the NTF is built, it should be routinely operational.

LEADING-EDGE SEPARATION

For a swept wing with a sharp leading edge or a small-radius leading edge, the flow at angle of attack is characterized by leading-edge separation with large conical vortices along the upper surface behind the leading edges on both wing panels. Within each vortex is an oppositely rotating secondary vortex, and detailed studies have shown still smaller inner vortices. With increasing angle of attack the leading-edge vortices increase in size until they "burst"; that is, the separation surface that starts at the leading edge and encloses the vortex now no longer returns to the upper surface of the wing, and the spinning, highly structured vortex flow is replaced by a low-energy, almost unstructured, stall flow.

These phenomena, including the forces, pressure distributions, and the angles of attack at which the vortices burst, are known to be influenced by Reynolds number. The NTF would be useful for studying these phenomena on various swept-wing configurations over a range of Reynolds numbers up to the highest values obtainable. Force tests, visual-flow studies, and flow surveys are all desirable.

HIGH-ANGLE-OF-ATTACK SEPARATION

An important area of research is separation on cylinders (with circular and other types of cross sections) at high angles of attack and at high Reynolds numbers. The subject is important with regard to the aerodynamics of fuselages and missiles (or launch vehicles), but it has received inadequate development. Available information indicates that scale effect is appreciable but less well understood than for wings. The studies should include flow visualization and measurements of local velocities along with forces and pressures.

High-angle separation on wings, both two- and three-dimensional, remains an important area for research. Because of the variety of airfoil sections and airplane configurations, however, a good choice for a research model is difficult to identify. At this time it may be best merely to recommend that such research be given high priority as particularly important airfoil sections or configurations arise, or when particular test models in the NTF become strongly involved with separation phenomena.

SHOCK-BOUNDARY LAYER INTERACTION

The pressure rise across a wing shock causes thickening or separation of the wing boundary layer. Even where separation does not occur, both analytical and experimental studies show large deviations of airfoil characteristics from the theoretical zero-viscosity characteristics. These scale effects have emphasized the desirability of extending the experimental studies of shock—boundary-layer interaction to the highest attainable Reynolds numbers. The unique ability of the cryogenic wind tunnel to isolate Mach number, Reynolds number, and aeroelastic effects is very important for shock–boundary–layer interaction studies on three-dimensional wings. In ambient temperature tunnels where the dynamic pressure varies with Reynolds number, the accompanying aeroelastic effects can completely mask the Reynolds number effects being studied.

The shock-boundary-layer interaction is also important for fuselages and nacelles, and especially for the afterbody boattails where the interaction is associated with large drag effects. There will doubtless be requests for the NTF to be involved with this important area of research, but any proposal will need an especially clear definition of purpose and approach. For example, if sting size and hence sting interference is minimized, the experiment, at least, is clearly defined, but the jet effect is not represented. At the other extreme, the jet might actually be modeled, as by a high-speed flow of warm nitrogen. Although there is a considerable body of experience relevant to this technique, it is difficult and troublesome at best, and urging the development of this technique at this time may not be reasonable.

STUDIES OF SUBMARINE SHAPES

The study of low-drag, low-noise submarine configurations is hampered by the Reynolds number limitations of available facilities. Some involvement in both force tests and basic flow studies of such configurations may be anticipated after the NTF becomes operational. This work, involving three-dimensional boundary layers and separation, would have general interest and applicability.

LOW-SPEED STUDIES OF CYLINDERS NORMAL TO FLOW

There remains considerable interest in the forces on large cylinders with their axes normal to the wind, not only for application to launch vehicles on the launch pads but also for application to various industrial shapes, such as smoke stacks and the large cylinders that shield off-shore oil-well drilling equipment.

Studies in 1969 in the Langley TDT of dynamic forces on a large cylinder gave results for static cylinders for Reynolds numbers up to 10×10^6 (in addition to results for oscillating cylinders). At this Reynolds number, most of the oscillating forces observed at the lower Reynolds numbers had died out, but one oscillating cross-wind force remained, with an amplitude that seemed to be gradually decreasing with increasing Reynolds number. It would be desirable to extend the data up to the highest Reynolds number attainable in the NTF at low Mach numbers. At $M = 0.2$, the NTF could provide a Reynolds number of 80×10^6 for a 50-cm-diameter test cylinder.

WALL-INTERFERENCE EFFECTS

In calibrating a new transonic tunnel, a considerable effort is put into studies of wall interference on the flow at the model, and into determining optimum wall slot design and slot setting, plenum-chamber pressure, etc., in order to minimize interference and optimize flow uniformity and tunnel efficiency. Analytical and experimental studies for the NTF are already under way and will presumably be continued and extended during the next 5 years. One should anticipate that after the NTF is put into operation, an especially large amount of time and effort will have to go into this phase of the calibration because the wall boundary-layer characteristics will vary widely with tunnel pressure and Mach number. Optimum wall slot settings will probably correspondingly vary from one situation to another.

Because of the large range of temperatures over which the NTF can operate, it will be possible to test geometrically similar models of different sizes at constant Mach number without changing Reynolds number or dynamic pressure. The ability to hold dynamic pressure constant serves to avoid the problem of model distortion due to changing model stresses between the various sizes of models. If the smallest model has negligible wall interference, then assessment of wall interference for the larger models will follow directly from comparison of the sets of data. Such a comparison would be especially significant for transonic testing in the case where the small model has a supersonic region over the wing that extends only a short distance from the surface, whereas the corresponding supersonic region over the large model approaches or extends to the tunnel wall. Programs such as these would further exploit the unique research capability of the NTF.

- High Reynolds number
- Independent control of:
  - Reynolds number (viscous effects)
  - Mach number (compressibility effects)
  - Dynamic pressure (aeroelastic effects)

Figure 1.- Some unique capabilities in cryogenic tunnels for fluid mechanics research.

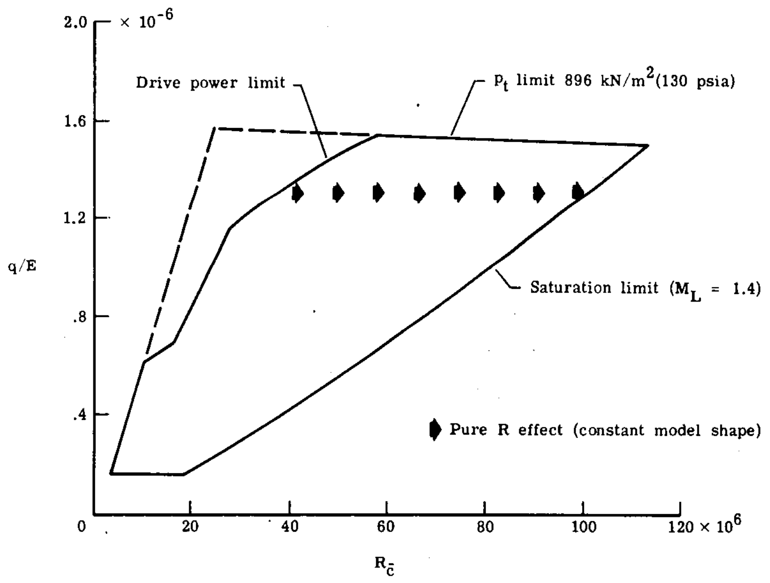

Figure 2.- NTF pure Reynolds number test capability. Steel models (9% Ni); M = 0.90; $\bar{c}$ = 0.25 m.

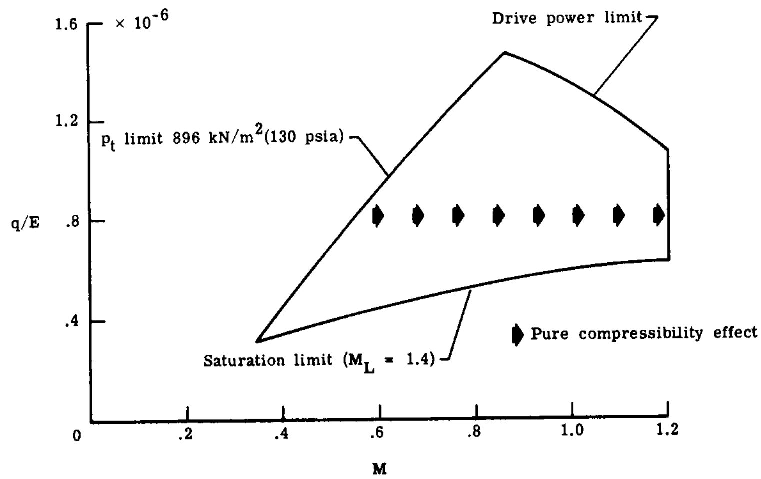

Figure 3.- NTF pure compressibility test capability. Steel models (9% Ni); $R_{\bar{c}} = 50 \times 10^6$; $\bar{c} = 0.25$ m.

- Basic problems
  - Turbulent boundary layers (including effects of 3-D flow and adverse pressure gradients)
  - Separated flows (resulting from adverse pressure gradients, shock-boundary-layer interactions, roughness/concavities, and 3-D effects)
  - Vortex flows (emanating from wings and fuselage noses at high angles of attack, from wing-fuselage junctions; multiple vortex interactions; vortex breakdown; vortex asymmetries)
- Evaluation and improvement of wind-tunnel test techniques
  - Fixed-transition correlations versus free-transition correlations
  - Wall boundary effects
  - Aeroelastic effects
  - Support interference effects
- Computational aerodynamics (empirical inputs and validation, e.g., turbulence modeling data)

Figure 4.- Fluid mechanics.

Effects of:

- Reynolds number
- Mach number
- Surface roughness
- Wall temperature
- Pressure gradient

Figure 5.- Turbulent skin friction.

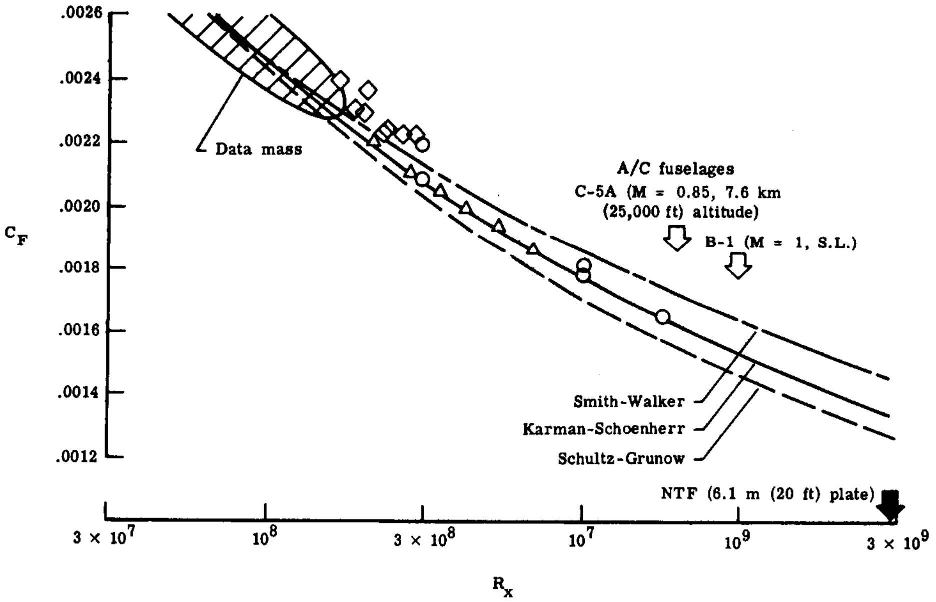

Figure 6.- Effect of Reynolds number on flat-plate skin friction.

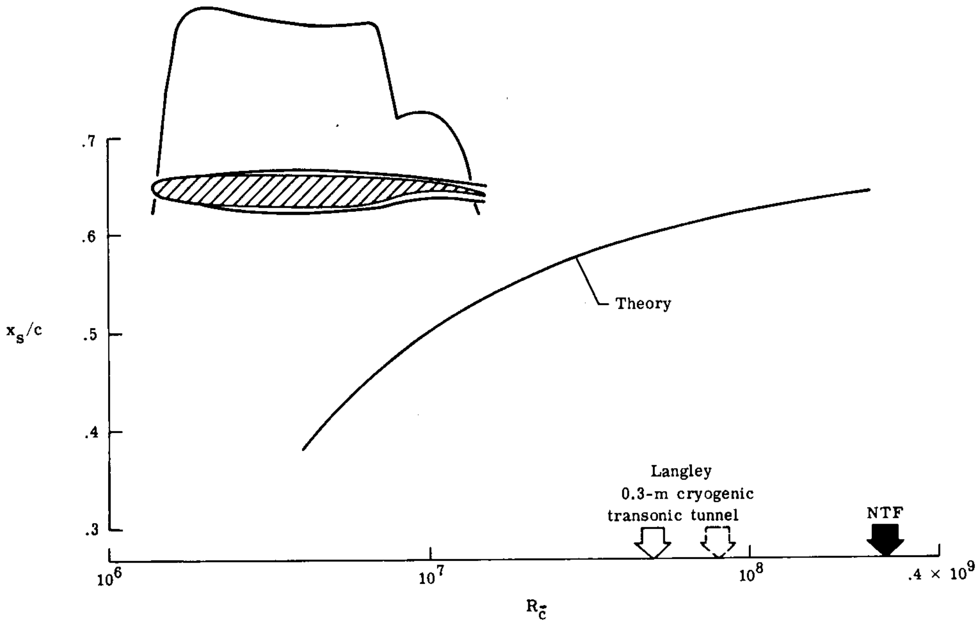

Figure 7.- Effect of Reynolds number on shock location.
Supercritical airfoil; M = 0.8.

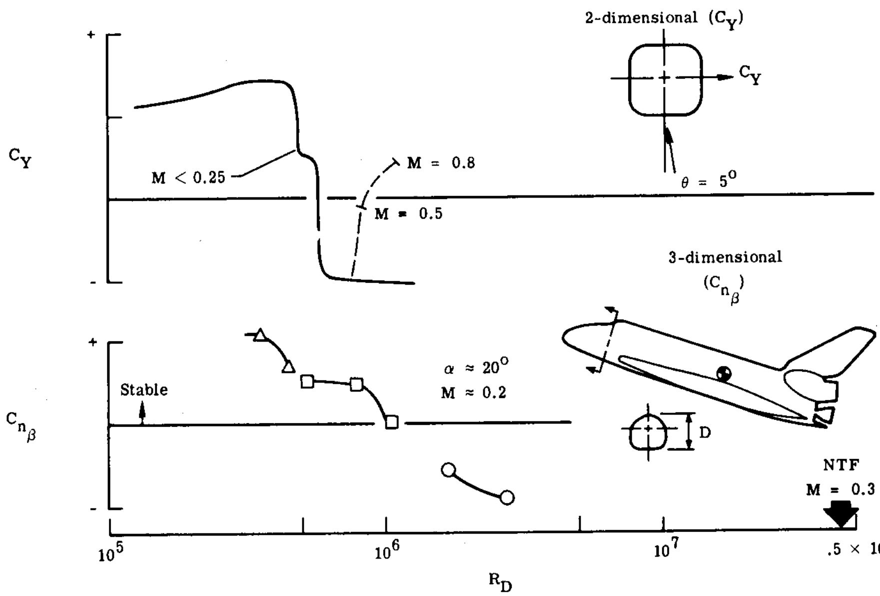

Figure 8.- Some effects of viscous cross flow.

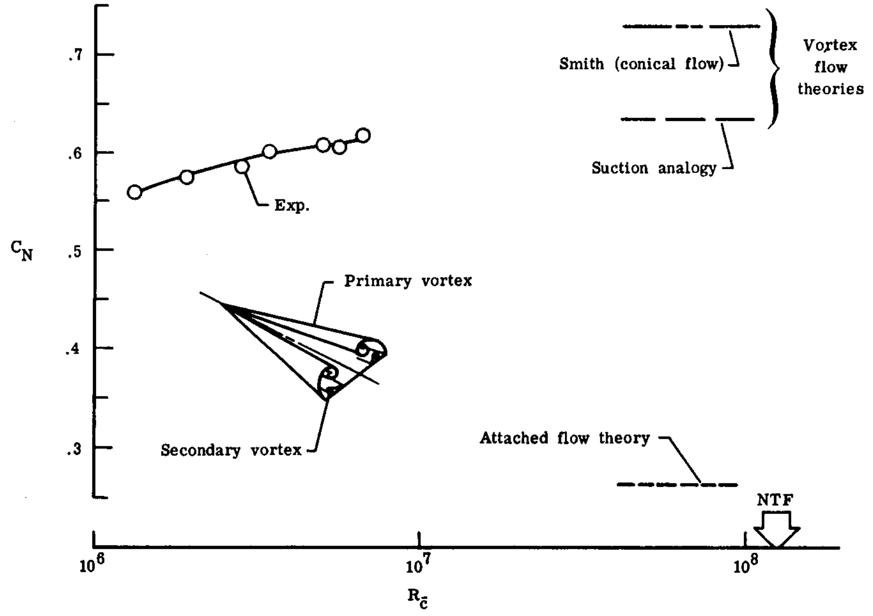

Figure 9.- Effect of Reynolds number on leading-edge vortex flow.
A = 0.52 delta; M = 0.90; $\alpha = 20^\circ$.

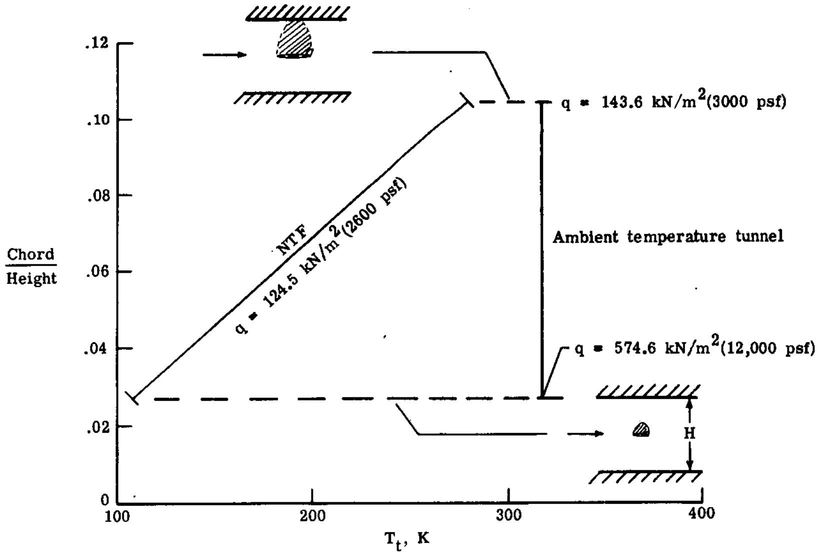

Figure 10.- NTF capability for wall interference studies.
M = 0.90; $R_{\bar{c}} = 15 \times 10^6$.

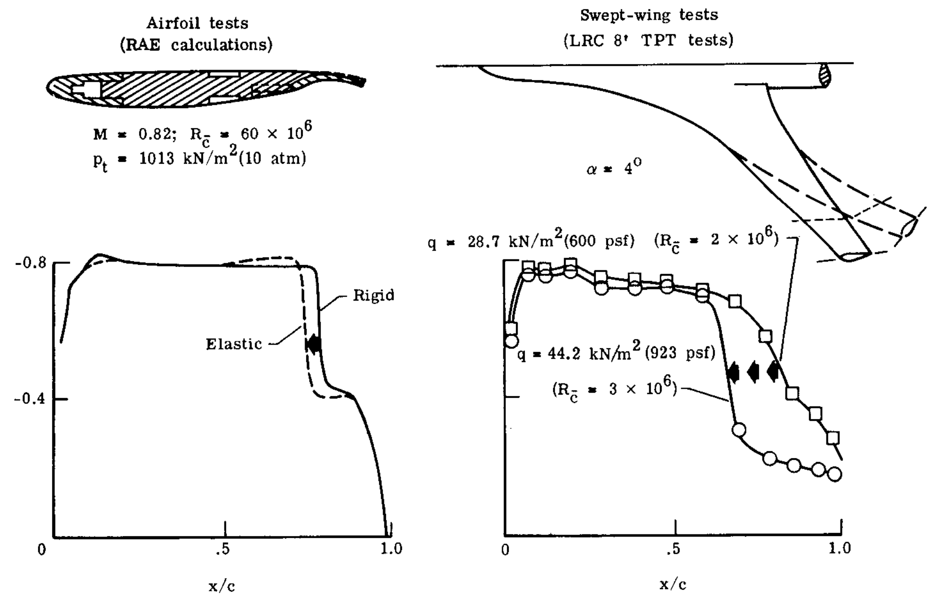

Figure 11.- Examples of aeroelastic problems in pressure tunnels. q varying with R.